Deep study of the fast bipolar outflows in pre-PNe from CO mm-wave line emission

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Summary. High spatial resolution images of PNe have shown their extremely complex morphology. However, the circumstellar envelopes of their progenitors, the AGB stars, are strikingly spherical. In order to understand the carving processes leading to axisymmetric nebulae, we are carrying out a study of a large sample of pre-PNe. Our emission model of the nebular molecular gas (^{12}CO & ^{13}CO) will allow us to determine important physical parameters (mass, linear momentum, kinetic energy) of the fast bipolar and slow spherical nebular components separately. We will study in an innovative way the properties for each source individually, and put our results in an evolutionary context with the help of the data obtained by us and collected from the literature.

Key words: stars: AGB and post-AGB – stars: circumstellar matter – radio-lines: stars – planetary nebulae

1 Introduction

During the latter stage of stellar evolution of low- and intermediate-mass stars, an striking transformation occurs in the nebular morphology and kinematics: the spherical, slowly expanding ($\sim 15\,\mathrm{km\,s^{-1}}$) circumstellar envelopes of AGB stars transform into highly aspherical PNe with fast outflows ($\sim 100\,\mathrm{km\,s^{-1}}$). High spatial resolution images of pre-PNe has shown that the asphericity is already present in practically all well-resolved sources [4]. In addition, the presence of fast bipolar outflows is a common feature in these objects [1]. The physical processes leading to the appearance of this fast wind are not clearly understood, and the possible link to other structural features such as disk or tori, or a companion star, remain unknown. Magnetic fields may also be involved in the formation of these outflows (see [2]).

CO emission is the best probe to study the kinematics of the nebular molecular gas, which is the majority of the total nebular mass. Using a synthetic model it is possible to obtain crucial information about the physical conditions of the nebula. CO emission lines of pre-PNe show a characteristic profile where two components are clearly distinguished: i) the core of the line at low velocity, mainly (but not only) corresponding to the spherical component of the nebula, which is probably the fossil AGB wind, and, ii) the wings of the line at high velocity, corresponding to the bipolar component of the nebula. Note that although the bipolar component is the only one detected at high velocities, this is also detected at low velocities because of projection effects.

The first systematic study of the physical characteristics of the bipolar outflows of pre-PNe from their CO emission was made by [1]. They considered that only the wings of the line represent the emission of the fast bipolar outflow, and, that all the fast gas flows in the direction of the nebula axis. To go a step further, besides increasing the number of sources in the sample with high-quality new observations, we have modeled the CO emission of the bipolar component of the nebula flowing in all directions. This way we are able to separate the CO emission at low velocities of the bipolar component from that of the spherical component at the core of the observed spectrum. This will help us to obtain more accurate values of the mass, the linear momentum, and the energy driven by the bipolar outflows, and to better understand whether those parameters are linked to other observational characteristics of these sources.

2 The sample

Table 1. List of sources included in our study.

IRAS Z02229+6208	IRAS 22223+4327	M 2–56	IRAS 19475+31
IRAS 06530–0213	OH 17.7–2.0	OH 231.8+4.2	IRAS 22272+5435
IRAS 07131–0147	IRAS 04296+3429	Hen 3-401	IRAS 22574+6609
IRAS 08005–2356	CRL 618	Roberts 22	IRAS 20000+3239
IRAS 18059–3211	Frosty Leo	HD 101584	IRAS 23304+6147
IRAS 18095+2704	IRAS 17436+5003	Boomerang Nebula	R Sct
IRAS 17438+5003	He 3-1475	He 2-113	IRAS 20028+3910
NGC 6302	IRAS 19500–1709	Mz-3	IRAS 23321+2545
89 Her	CRL 2477	M 2–9	IRAS 17150–3224
IRAS 07134+1005	CRL 2688	CPD -568032	IRAS 21282+5050
Red Rectangle	NGC 7027	M 1–92	

We have a sample of 43 sources (see Table 1), most of them observed in ^{12}CO and ^{13}CO, both in transitions J=1–0 and J=2–1, at Pico de Veleta (Spain). The data corresponding to the rest of the sources are taken from the literature. With this large sample of sources it is possible to improve the statistical study on the characteristics found for their different nebular components.

3 Model

Starting with a few assumptions we have modeled the expected ^{12}CO and ^{13}CO emission profiles from the bipolar component of pre-PNe. These assumptions were:

- $\boldsymbol{V}_{\mathrm{exp}} \propto \boldsymbol{r}$, i.e., Hubble expansion velocity law
- Axial symmetry, ellipsoidal or bilobal
- Optically thin emission

We consider that the CO gas is confined to an infinitesimally thin shell. Assuming mass conservation and an originally isotropical distribution of mass, we have a scenario similar to an anisotropically expanding balloon, where, as it expands the density at each point decreases following $\rho \propto r^{-2}$.

In our model, the CO gas located in the region closer to the star has low V_{exp}, that would correspond to the slow spherical component. Thus, in order to avoid such CO gas when computing the fast bipolar component emission profile, we have introduced a lower limit to V_{exp}, V_{AGB}.

4 Application of the model. The case of CRL 2688

In order to test our model, we have applied it to a well studied source included in our sample, CRL 2688. First we obtain from the bibliography the values of some input parameters of our model: i) the inclination with respect to the plane of the sky, ii) the ratio between the mayor an the minor axis of the nebula, and iii) the distance to the source. We estimate the value of V_{AGB} from the width of the core of the observed emission line, and the rotational temperature from the observed line intensity ratio. Once all these data are obtained, we fit by a χ^2 method our synthetic profile of the bipolar component to the wings of the observed profile. This way we obtain the only two free parameters: the mass and the maximum expansion velocity of the bipolar component. After a successfully fit is obtained, we are able to obtain the mass of the spherical component of the nebula just by subtracting the bipolar component mass to the total mass. The model is preferably fitted, in the cases in which it is possible, to ^{13}CO lines, since they are optically thinner than those of ^{12}CO. A factor can be introduced as a correction due to opacity and calibration effects.
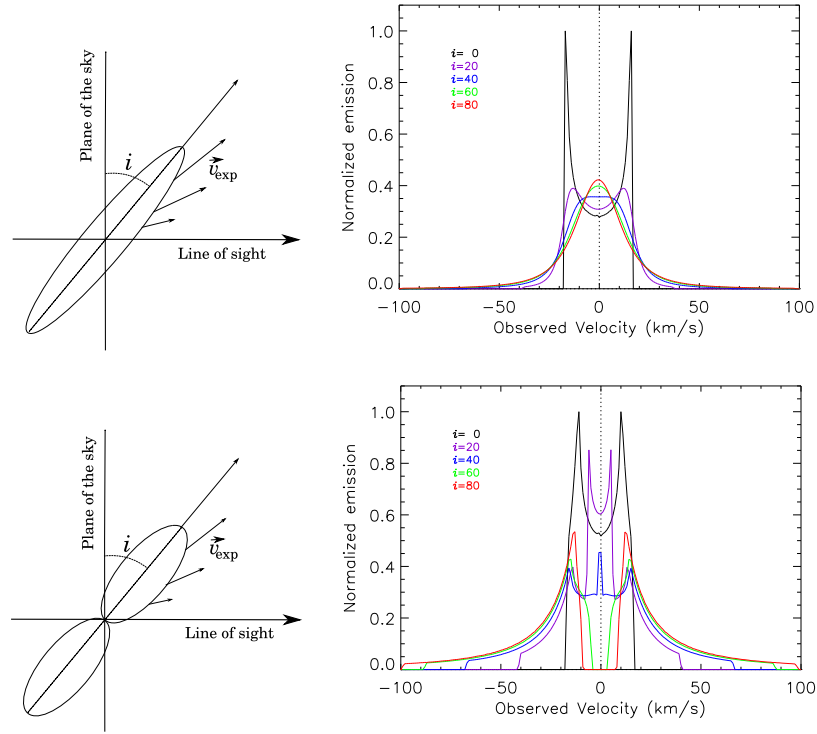
Fig. 1. *Left:* Geometry scheme. *Right:* variation of the expected CO emission profiles from the bipolar component with the inclination of the nebula with respect to the plane of the sky. *Up:* Ellipsoidal geometry. *Down:* Bilobal geometry
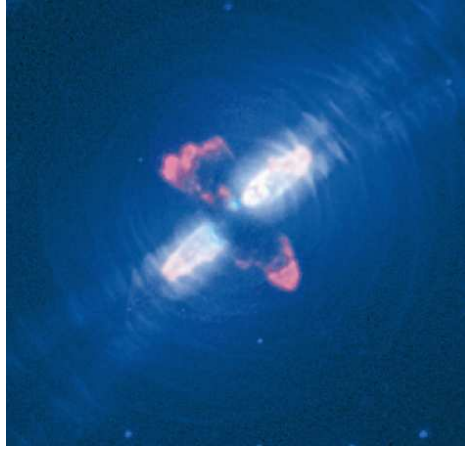
Fig. 2. Near-infrared image of CRL 2688 from [3].
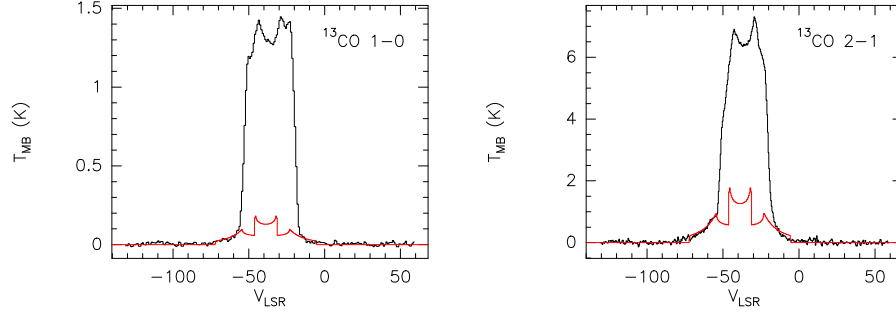
Fig. 3. Results of the model fitting for the wings of the profiles of CRL 2688. We have obtained, assuming bilobal geometry, a maximum expansion velocity of $100 \, \mathrm{km \, s^{-1}}$ and a mass of $0.11 M_\odot$ for the bipolar component. Note the good correlation between the synthetic profile of the bipolar component and the two observed peaks in the core of the line.

The results obtained for CRL 2688 are compatible with those obtained by [1]. For this source they deduce a mass for the bipolar outflows of $0.06 M_\odot$, while we obtain $0.11 M_\odot$. The main reason for this difference is that we have not taken into account only the wings of the spectra as the emission of the bipolar component, but also the important contribution of the emission at low projected velocities, which is hidden by the most intense emission of the spherical component at the core of the line.

5 Future work

We will use this innovative model and new observational data to obtain the main physical characteristics of the fast bipolar outflows of pre-PNe. Our large sample will help us to find possible relations between them and other observational characteristics already known for these source, and therefore, to obtain a better understanding of how the fast collimated bipolar outflows are formed.

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